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Meta-analysis of no-tillage effect on wheat and maize water use efficiency in China

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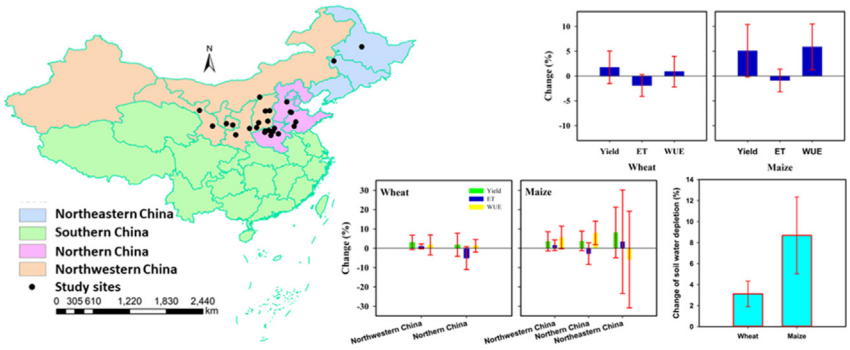
HIGHLIGHTS

- Evaluation of no tillage (NT) effects on WUE of wheat and maize in China.
- NT increased maize WUE by 5.9% across 155 paired observations.
- WUE responses to NT were affected by species, region, climate, agronomic practices.
- Site-specific adoption of NT is needed to improve WUE.

GRAPHICAL ABSTRACT



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ABSTRACT

No-tillage (NT) is a popular agricultural technique worldwide, but it remains unclear how NT affects the yield, evapotranspiration (ET), and water use efficiency (WUE) of maize and wheat. We performed a meta-analysis of the NT effects on the yield, ET and WUE for wheat and maize based on the literatures published during 1950–2018. Yield, ET, and WUE varied by species, region, and agronomic and environmental factors. Averaged across all the geographic locations NT had no effect on the yield, ET, or WUE of wheat in northwestern and northern China, and no effect on the yield or ET of maize, but significantly increased the maize WUE by 5.9%. NT increased the WUE and yield of wheat in regions with ≤400 mm of mean annual precipitation, increased the yield in regions with 400–600 mm of precipitation, and decreased the yield and ET in regions with ≥600 mm, but had no effects on maize. In the first 1–3 years of NT implementation, the wheat ET was reduced. However, a significant decrease in maize yield and ET occurred in 3–6 years of NT implementation. Meanwhile, yield and WUE in both wheat and maize were improved after >6 years. In general, NT effect on yield, ET, or WUE was not related to soil texture. However, NT increased maize WUE in a medium soil texture. Without crop rotation, NT increased wheat yield and ET but decreased maize yield. No NT effects were observed when crop residues retained and under crop rotation. Consequently, optimizing NT effects on yield, ET and WUE for wheat and maize in China was largely dependent on environmental conditions and management practices.

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1. Introduction

Cereal grains have nourished humanity since their domestication thousands of years ago and remain the most important source of energy

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for the majority of the human population (Daryanto et al., 2016). The global demand for major grains, such as maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.), is projected to increase by 70% by 2050 (Nelson et al., 2010). To ensure the world's future food security and meet sustainability needs, food production must grow substantially (Foley et al., 2011). High-yield conventional agriculture has been largely characterized by high rates of fossil fuel energy consumption, excessive nutrient use, water pollution, and conventional tillage (CT), namely, plowing followed by harrowing, which leaves soil vulnerable to erosion (Farooq et al., 2011; Foley et al., 2011). CT requires a large amount of labor, which has been difficult to find in recent years due to agricultural labor migration in China, and has been further compounded by degraded soil resources (Montgomery, 2007). Therefore, it is imperative to produce greater yields with fewer resources, and no-tillage (NT) cultivation is being promoted to accomplish these goals in China.

NT, as one of three crop management principles (FAO, 2011), involves sowing crops in untilled soil by opening a narrow slot or trench of sufficient depth to provide proper seed coverage (Phillips and Young, 1973), which has the potential benefits of labor savings and soil conservation (Uri, 1997). Many field experiments have been conducted recently to examine the effects of NT on wheat and maize production in China. In one study, winter wheat and summer maize yields tended to be higher under no/reduced tillage compared to CT without crop straw retention (He et al., 2011), whereas Chen et al. (2011) showed that NT significantly decreased maize yield. Wang et al. (2012) reported that, compared to conventional methods, reduced tillage increased yields approximately 13–16% in spring maize and approximately 9–37% in winter wheat, while yields under NT were similar to those of conventional methods used in northern China. Currently in China, as exemplified by these studies, the effects of NT on wheat and maize yield and ET do not show consistent results.

Regarding the effects of NT on water usage, the evapotranspiration (ET) values under plow-tillage were higher than those of NT from the sowing to flowering stages, but significantly lower at the ripening stage (Guan et al., 2014). In another study, there was more soil water in the 0–30-cm soil layer during sowing under NT with retained stubble treatment than under CT with removed stubble treatment for both field pea (60 mm vs. 55 mm) and spring wheat (60 mm vs. 53 mm) in a semi-arid environment (Huang et al., 2008). Meanwhile, soil water storage was higher under NT with crop residue mulch compared to other treatments, which included traditional tillage, in the Loess Plateau (Zhang et al., 2011a). Water use efficiency (WUE) is the ratio of yield and ET (Zhang et al., 2013), and describes water consumption and related soil water storage. There is much uncertainty regarding how NT affects the WUE of crops. Moreover, the effects of NT on WUE may be affected by yield, which could be the result of its effects on soil properties (Tesfahunegn, 2015) that also affect soil water storage.

The effects of NT on crop yield, ET, and WUE are dependent on several co-varying factors [i.e., agro-climatic regions, soil texture, no-till duration (NTD), irrigation, crop residue management, and rotation]. One analysis documented the effects of NT on rice yield in China, and concluded that yields did not decrease (Huang et al., 2015), and a global meta-analysis showed that NT yields matched CT yields for oilseed, cotton, and legume crops (Pittelkow et al., 2015a).

The effects of NT on the yield, ET, and WUE of wheat and maize have not been quantified in China across a range of agro-ecological conditions. Because conditions often vary among site-specific field experiments, a meta-analysis is useful for summarizing the results from numerous independent experiments on NT (Hedges et al., 1999). Therefore, the main objective of this study was to (1) investigate the effects of NT on the yield, ET, and WUE of wheat and maize in China and (2) determine how the effects vary with environmental and management factors via a meta-analysis of published studies.

2. Materials and methods

2.1. Data search and selection criteria

A meta-analysis was conducted to characterize the response of wheat and maize yield, ET, and WUE to NT in China. Data were extracted from studies where CT (control) could be compared to the paired NT treatment in China. To determine the agro-climatic regions, soil texture, and management factors affecting the responses of wheat and maize yield, ET, and WUE to NT in China, the experiments were grouped in terms of experimental location, mean annual precipitation (MP), mean annual air temperature (MT), soil texture, NTD (i.e., the number of years from the beginning to the end of the experiment), water supply (irrigated or rainfed), residue management, and crop rotation.

We collected peer-reviewed journal articles published during 1950–2018 and built a database of wheat and maize yield, ET, and WUE. The database was created using the China National Knowledge Infrastructure, Web of Knowledge databases and Elsevier Science Direct with the following two sets of keywords: (i) wheat or maize, tillage, water use efficiency, yield, and field or (ii) wheat or maize, water use efficiency, no-till, yield, and field.

The articles included in the database met the following criteria: (a) studies were conducted under field conditions (excluding plot studies and greenhouse experiments) in China and (b) the reported plants were monoculture cereals including maize (*Zea mays* L.) or wheat (i.e., bread wheat; *Triticum aestivum* L.). The process was conducted following the flowchart diagram presented in Fig. 1 from Moher et al. (2009), and 53 published articles were identified (Table 1 and S1 Information).

When only yield and ET data were provided in articles without WUE data, the WUE was calculated with the formula WUE = Yield/ET. Some articles only provided yield and WUE data without ET data. When results were only provided in graphical format, the required data were extracted from the figures using the Data Thief III program (Tummers, 2006). Standard deviation was used as the measure of variance, and was obtained or calculated from the published measure of variance in each study if necessary. We actually obtained all the missing data or part of them from the corresponding authors when no measures of variance are available.

The research in these articles was carried out in nine provinces or municipalities (Gansu, Ningxia, Shaanxi, Shanxi, Hebei, Shandong, Henan, Heilongjiang, and Jilin). The distribution of the study locations was generated using ArcGIS 10.2 (Fig. 2) (ESRI, Redlands, CA).

2.2. Building the datasets

Data were grouped to maximize in-group homogenization. The crop type included wheat and maize. The experimental regions included northwestern, northern, and northeastern China (Fig. 2, Table 2) as used by Zheng et al. (2014). MP was divided into three classes, ≤400 mm, 400–600 mm, and ≥600 mm (Zheng et al., 2014). MT was divided into two classes, ≤12 °C and ˃12 °C. Soil texture was grouped into three basic classes (coarse, medium, and fine) according to Daryanto et al. (2015). The NTD was divided into three classes (1–3 years, 3–6 years, and 6+ years) as used by Huang et al. (2015). The irrigation pattern was categorized as rainfed or irrigated. The residue management practice was categorized as removed or retained, and crop rotation was categorized as crop rotation or no rotation according to Pittelkow et al. (2015b).

2.3. Data analysis

2.3.1. Meta-analysis

The yield attribute data of the NT and CT treatments were extracted from the selected articles as response variables and included yield, ET,

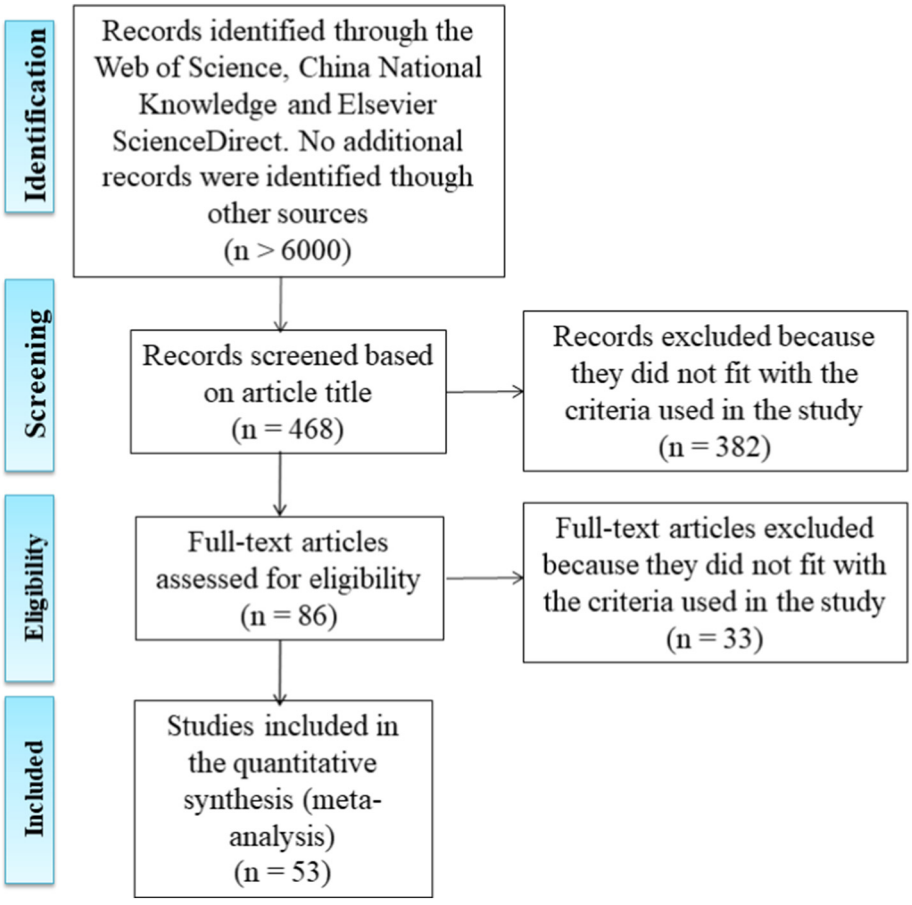
Identification
Records identified through the Web of Science, China National Knowledge and Elsevier ScienceDirect. No additional records were identified though other sources (n > 6000)
Screening
Records screened based on article title (n = 468)
Records excluded because they did not fit with the criteria used in the study (n = 382)
Eligibility
Full-text articles assessed for eligibility (n = 86)
Full-text articles excluded because they did not fit with the criteria used in the study (n = 33)
Included
Studies included in the quantitative synthesis (meta-analysis) (n = 53)

Fig. 1. Flowchart diagram of the process used to obtain the literature data to build a database for the study.

and WUE. We used the natural log of the response ratio (ln*R*) as a measure of effect size:

$$\ln R = \ln\left(\frac{X_N}{X_C}\right) \quad (1)$$

where X_N and X_C are the measured values of the response variable under NT and CT, respectively (Hedges et al., 1999).

A meta-analysis was performed using an unweighted function. The effect sizes were weighted based on the number of replicates. To avoid bias toward studies reporting results for multiple years, the weight of each effect size was divided by the number of years the data from the corresponding study included:

$$W_i = \frac{n}{y} \quad (2)$$

where W_i is the weight for the i effect size, n is the number of field replicates, and y is the number of years included in the dataset from the study corresponding to the i comparison.

The mean effect sizes were estimated as follows:

$$\ln^{-}R = \frac{\sum(\ln R_i \times W_i)}{\sum W_i} \quad (3)$$

where $\ln R_i$ is the effect size of the i comparison and W_i is the same as in Eq. (2).

The Stata software package (ver. 12.0; Stata Corp., College Station, TX, USA) was used to calculate mean effect sizes and generate bias-corrected 95% confidence intervals (CIs) for each mean effect size with a metan procedure.

To simplify the interpretation, the effect size (ES, %) was expressed as the percentage change, which was estimated as follows:

$$ES = (R-1) \times 100\% \quad (4)$$

A negative (or positive) percentage change indicated a decrease (or increase) in the response variable under NT relative to CT. The mean percentage change was considered to differ significantly from zero if the 95% CI did not overlap with zero (Hedges et al., 1999).

2.3.2. Correlation analysis

The correlation analysis was performed following the PROC CORR procedure (SAS Institute Inc., 2013) to test the relationships between the ln*R* of WUE with the ln*R* of yield and ET under site-specific conditions (i.e., experimental region, MP, MT, soil texture, NTD, irrigation pattern, residue management, and crop rotation management) for wheat and maize.

3. Results

Averaged across all geographic locations, NT had no apparent impact on wheat yield, ET, or WUE (Fig. 3A), or on maize yield or ET, but significantly increased maize WUE by 5.9% (Fig. 3B). Overall, yield and WUE showed a positive response to NT for wheat and maize, while ET showed a negative response to NT (Fig. 3). The ln*R* of WUE was significantly and positively related to the ln*R* of yield for wheat ($P < 0.0001$) and maize ($P < 0.0001$), and there was a significant ($P < 0.01$) negative relationship between the ln*R* of WUE and ET for maize (Table 3), indicating that the increase in maize WUE under NT was related to the increase in yield and decrease in ET compared to CT.

Table 1
Characteristics of the studies used in the meta-analysis.

Crop	Reference	Location	MP (mm)	MT (°C)	Soil texture	NTD (years)	Irrigation pattern	Residue management	Crop rotation	NC of yield	NC of ET	NC of WUE
Wheat	Chu et al. (2012)	Shandong	685	13.8	Medium	2	Irrigated	Retained	Rotation	6	6	6
	Guan et al. (2014)	Hebei	562	15.5	Medium	2	Rainfed	Retained	Rotation	3	3	3
	Han et al. (2011)	Shandong	666	13.0	Medium	7	Rainfed	Retained	No rotation	4	0	0
	He et al. (2009)	Gansu	552	11.7	Medium	2	Irrigated	Retained	Rotation	4	4	4
	Hou et al. (2009)	Ningxia	435	6.1	Coarse	1	Rainfed	Retained	Rotation	3	3	3
	Hou et al. (2011)	Ningxia	435	8.1	Coarse	4	Rainfed	Removed	No rotation	15	15	15
	Hou et al. (2012a)	Ningxia	435	8.1	Coarse	4	Rainfed	Removed	No rotation	18	18	18
	Hou et al. (2012b)	Ningxia	435	8.1	Coarse	4	Rainfed	Removed	No rotation	18	18	18
	Hu et al. (2016)	Gansu	160	7.2	Coarse	2	Irrigated	Retained	Rotation	3	0	0
	Huang et al. (2008)	Gansu	391	11.7	Coarse	5	Rainfed	Removed	Rotation	5	0	5
	Huang et al. (2008)	Gansu	391	11.7	Coarse	6	Rainfed	Retained	Rotation	5	0	5
	Huang et al. (2012)	Gansu	174	7.8	Coarse	3	Irrigated	Removed	No rotation	3	3	3
	Huang et al. (2012)	Gansu	174	7.8	Coarse	4	Irrigated	Retained	No rotation	3	3	3
	Ji et al. (2014)	Shaanxi	600	13.0	Fine	12	Irrigated	Removed	Rotation	3	3	3
	Ji et al. (2014)	Shaanxi	600	13.0	Fine	12	Irrigated	Retained	Rotation	3	3	3
	Jin et al. (2007a)	Henan	600	13.7	Medium	30	Rainfed	Retained	Rotation	15	5	5
	Jin et al. (2007b)	Shanxi	555	10.7	Medium	8	Irrigated	Retained	No rotation	14	0	11
	Kong et al. (2014)	Hebei	513	12.1	Medium	2	Irrigated	Retained	Rotation	6	6	6
	Li et al. (2006)	Henan	600	13.7	Medium	7	Rainfed	Retained	Rotation	3	3	3
	Li et al. (2014a)	Gansu	552	11.7	Coarse	16	Rainfed	Retained	Rotation	9	9	9
	Li et al. (2014b)	Henan	600	13.7	Fine	7	Rainfed	Retained	Rotation	3	0	0
	Niu et al. (2016)	Gansu	391	6.7	Coarse	16	Rainfed	Retained	Rotation	6	0	0
	Sang et al. (2014)	Shandong	685	13.8	Fine	1	Rainfed	Retained	Rotation	6	6	6
	Shi et al. (2016)	Shandong	685	13.8	Medium	7	Irrigated	Retained	Rotation	5	0	0
	Su and Zhao, (1999)	Henan	659	14.0	Coarse	2	Rainfed	Retained	Rotation	3	3	3
	Su et al. (2007)	Henan	614	13.7	Medium	7	Rainfed	Retained	No rotation	7	7	7
	Sun et al. (2014)	Shanxi	440	11.0	Medium	3	Rainfed	Removed	No rotation	3	0	3
	Sun et al. (2018)	Shaanxi	538	10.5	Fine	9	Rainfed	Retained	No rotation	6	6	6
	Sun et al. (2018)	Shanxi	491	12.9	Medium	7	Rainfed	Retained	Rotation	3	3	3
	Wang and Li (2016)	Shaanxi	538	11.5	Fine	5	Rainfed	Retained	No rotation	6	6	6
	Wang et al. (2004)	Henan	600	13.7	Coarse	2	Rainfed	Retained	No rotation	3	0	3
	Wang et al. (2012)	Henan	570	14.6	Coarse	5	Rainfed	Retained	No rotation	3	3	3
	Wang et al. (2012)	Shanxi	450	12.1	Fine	5	Rainfed	Retained	No rotation	3	3	3
	Wang et al. (2012)	Shanxi	550	9.4	Medium	5	Rainfed	Retained	No rotation	3	3	3
	Yang et al. (2017)	Henan	598	15.0	Coarse	3	Rainfed	Retained	Rotation	6	0	6
	Yang et al. (2014)	Henan	682	14.2	Fine	1	Rainfed	Removed	Rotation	3	3	3
	Zhang et al. (2011a)	Shaanxi	538	11.5	Fine	6	Rainfed	Retained	Rotation	6	6	6
	Zhang et al. (2012)	Henan	579	14.7	Coarse	10	Rainfed	Retained	Rotation	24	0	0
	Zhang et al. (2015)	Shaanxi	538	11.5	Fine	29	Rainfed	Retained	Rotation	3	0	3
	Zhang et al. (2017)	Gansu	540	8.3	Coarse	11	Rainfed	Retained	No rotation	15	15	15
	Zhao et al. (2014)	Henan	552	14.3	Fine	2	Irrigated	Removed	Rotation	3	0	3
	Zhao et al. (2014)	Henan	552	14.3	Fine	2	Irrigated	Retained	Rotation	3	0	6
	Zheng et al. (2014)	Shandong	685	13.8	Medium	4	Rainfed	Retained	Rotation	6	3	3
Maize	Bian et al. (2000)	Jilin	378	5.9	Fine	2	Rainfed	Removed	No rotation	3	0	5
	Chen et al. (2011)	Heilongjiang	550	1.5	Fine	7	Rainfed	Retained	Rotation	4	0	3
	Chen et al. (2013)	Shaanxi	588	12.9	Fine	1	Rainfed	Removed	No rotation	3	3	3
	Chen et al. (2013)	Shaanxi	588	12.9	Fine	1	Rainfed	Retained	No rotation	3	3	5
	Guo et al. (2012)	Shaanxi	365	7.1	Coarse	6	Rainfed	Retained	No rotation	20	3	12
	He et al. (2009)	Hebei	552	11.7	Medium	3	Irrigated	Retained	Rotation	10	10	0
	Hu et al. (2016)	Gansu	160	7.2	Coarse	2	Irrigated	Retained	Rotation	3	0	3
	Ji et al. (2014)	Shaanxi	600	13.0	Fine	12	Irrigated	Removed	Rotation	3	3	3
	Ji et al. (2014)	Shaanxi	600	13.0	Fine	12	Irrigated	Retained	Rotation	3	3	5
	Jin et al. (2007a)	Hebei	552	11.7	Medium	8	Irrigated	Retained	Rotation	6	0	0

(continued on next page)

Table 1 (*continued*)

Crop	Reference	Location	MP (mm)	MT (°C)	Soil texture	NTD (years)	Irrigation pattern	Residue management	Crop rotation	NC of yield	NC of ET	NC of WUE
	Jin et al. (2007b)	Shanxi	515	7.3	Medium	8	Irrigated	Removed	No rotation	8	0	8
	Kong et al. (2014)	Hebei	513	12.1	Medium	2	Irrigated	Retained	Rotation	6	6	0
	Li et al. (2014b)	Henan	600	13.7	Fine	7	Rainfed	Retained	Rotation	3	0	5
	Liu et al. (2013)	Heilongjiang	550	1.5	Fine	8	Rainfed	Retained	Rotation	3	0	3
	Liu et al. (2014)	Heilongjiang	550	1.5	Fine	3	Rainfed	Retained	Rotation	3	3	3
	Liu et al. (2014)	Heilongjiang	550	1.5	Fine	9	Rainfed	Retained	Rotation	3	0	3
	Liu et al. (2014)	Heilongjiang	550	1.5	Fine	10	Rainfed	Retained	Rotation	3	0	3
	Liu et al. (2014)	Heilongjiang	550	1.5	Fine	11	Rainfed	Retained	Rotation	3	0	3
	Sun et al. (2018)	Shaanxi	538	10.5	Fine	9	Rainfed	Retained	No rotation	6	6	6
	Wang and Li (2016)	Shaanxi	538	11.5	Fine	5	Rainfed	Retained	No rotation	6	6	8
	Wang et al. (2011)	Shanxi	459	7.4	Coarse	8	Rainfed	Retained	No rotation	6	0	3
	Wang et al. (2012)	Shanxi	550	9.4	Medium	5	Rainfed	Retained	No rotation	3	3	0
	Wang et al. (2012)	Shanxi	520	7.4	Coarse	5	Rainfed	Retained	No rotation	3	3	3
	Wang et al. (2015)	Shanxi	452	7.4	Coarse	11	Rainfed	Removed	No rotation	12	0	12
	Wang et al. (2016)	Shanxi	553	11.5	Medium	7	Rainfed	Retained	Rotation	5	0	0
	Yang et al. (2017)	Henan	598	15.0	Coarse	3	Rainfed	Retained	Rotation	3	0	3
	Zhang et al. (2000)	Hebei	554	12.5	Medium	2	Rainfed	Retained	Rotation	3	3	3
	Zhang et al. (2000)	Hebei	554	12.5	Medium	2	Irrigated	Retained	Rotation	3	3	3
	Zhang et al. (2011b)	Shaanxi	538	11.5	Fine	7	Rainfed	Retained	Rotation	3	3	5
	Zhang et al. (2011a)	Shaanxi	578	9.3	Medium	3	Rainfed	Removed	No rotation	3	3	3
	Zhao et al. (2014)	Henan	552	14.3	Fine	2	Irrigated	Removed	Rotation	3	0	3
	Zhao et al. (2014)	Henan	552	14.3	Fine	2	Irrigated	Retained	Rotation	3	0	0
	Zhou et al. (2018)	Gansu	570	9.0	Coarse	7	Rainfed	Retained	Rotation	3	0	3

MP: mean annual precipitation from each reference; MT: mean annual air temperature from each reference; NTD: No-tillage duration; NC: Number of comparisons.

3.1. Yield, ET, and WUE impacts by region and climate

The responses of yield, ET, and WUE to NT varied by region and climate for wheat (Fig. 4). NT had no effect on wheat yield, ET, or WUE in northwestern and northern China (Fig. 4A, B). Meanwhile, NT significantly increased wheat yield (7.2%) and WUE (7.9%), but had no effect on ET compared with CT in regions with an MP ≤ 400 mm (Fig. 4C). We found a significant increase of 5.1% in the wheat yield under NT, but no

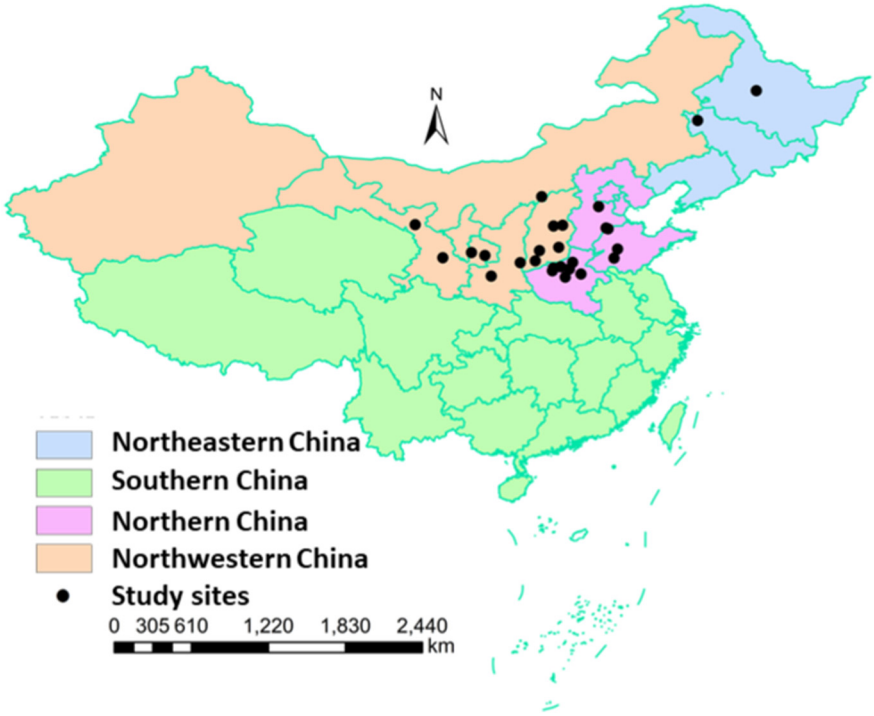

Fig. 2. Distribution of the locations of the studies included in the meta-analysis. The map was generated using ArcGIS 10.2.

Table 2
Distribution of the geographic locations of the study sites.

Crop group	Region	Province	No. of data points	Percentage of total data points (%)
Wheat	Northwestern China	Gansu Province Ningxia Hui Autonomous Region Shaanxi Province Shanxi Province	163	59.3
	Northern China	Hebei Province Shandong Province Henan Province	112	40.7
Maize	Northwestern China	Gansu Province Ningxia Hui Autonomous Region Shaanxi Province Shanxi Province	93	60.0
	Northern China	Hebei Province Shandong Province Henan Province	40	25.8
	Northeastern China	Heilongjiang Province Jilin Province	22	14.2

effects of NT on ET or WUE compared with CT in regions with an MP of 400–600 mm (Fig. 4D). NT significantly decreased wheat yield and ET, but had no effect on WUE in regions with an MP of ≥600 mm (Fig. 4E). NT had no effects on yield, ET, or WUE in regions with MTs ≤ 12 °C or >12 °C (Fig. 4F, G). In addition, the ln*R* of WUE was significantly ($P < 0.01$) positively correlated with the ln*R* of yield, and there was a significant negative relationship between the ln*R* of WUE and ET for wheat in regions with an MP ≤ 400 mm ($P < 0.01$) (Table 3). These results indicated that the increase in wheat WUE under NT in regions with an MP of ≤400 mm was due to the increase in yield and the decrease in ET.

The ln*R* values of yield, ET, and WUE under NT varied by region and climate for maize (Fig. 4). NT had no effects on maize yield, ET, or WUE in northwestern China (Fig. 4H). NT significantly increased WUE by 7.9%, but had no effect on yield or ET compared with CT in northern China (Fig. 4I). NT did not affect yield, ET, or WUE in northeastern China (Fig. 4J) or in regions with an MP ≤ 400 mm (Fig. 4K). NT significantly increased the WUE by 4.9%, but had no effects on yield or ET compared with CT in regions with an MP of 400–600 mm (Fig. 4L). We found no effects on yield, ET, or WUE in regions with MTs ≤ 12 °C or >12 °C (Fig. 4M, N). Meanwhile, the ln*R* of WUE was significantly positively related with the ln*R* of yield, and there was a significant negative relationship between the ln*R* of WUE and the ln*R* of ET in northern China (Table 3), indicating that the increase in WUE was related to the increase in yield and decrease in ET.

The error bars represent the 95% CI. The number of observations is indicated below the CI.

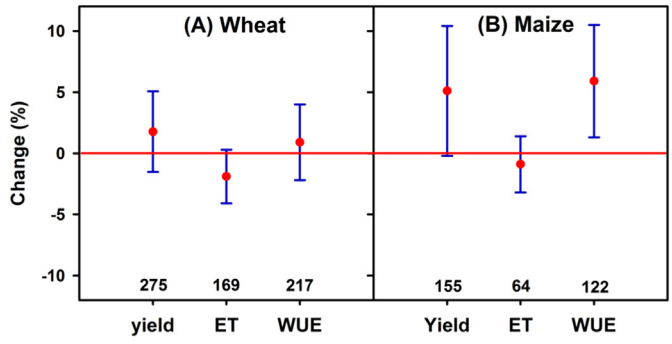

Fig. 3. Percentage changes in the yield, ET, and WUE of (A) wheat and (B) maize under NT compared to CT across a range of environmental and management conditions in China. The error bars represent the 95% CI. The number of observations is indicated below the CI.

Table 3
Correlation coefficients between the ln*R* values of WUE with those of yield and ET under different environmental and management factors.

Factor		Wheat		Maize	
		Yield	ET	Yield	ET
Grand		0.86^{****}	0.30^{ns}	0.89^{****}	-0.81^{**}
Region	Northwestern China	0.76^{**}	0.13^{ns}	0.96^{****}	-0.68^{*}
	Northern China	0.88^{****}	-0.12^{ns}	0.91^{****}	-0.82^{**}
	Northeastern China	\	\	0.71^{ns}	0.12^{ns}
MP	≤400 mm	0.79^{**}	-0.70^{**}	0.89^{***}	-0.79^{**}
	400–600 mm	0.91^{****}	0.16^{ns}	0.86^{****}	-0.69^{**}
	≥600 mm	0.76^{**}	0.12^{ns}	\	\
MT	≤12 °C	0.89^{****}	-0.18^{ns}	0.81^{**}	-0.41^{ns}
	>12 °C	0.76^{***}	0.13^{ns}	0.91^{**}	-0.45^{ns}
Soil texture	Coarse	0.93^{****}	0.21^{ns}	0.78^{**}	-0.32^{ns}
	Medium	0.66^{*}	0.25^{ns}	0.73^{**}	-0.31^{ns}
	Fine	0.31^{ns}	-0.16^{ns}	0.93^{****}	-0.22^{ns}
NTD	1–3 years	0.81^{**}	-0.16^{ns}	0.99^{****}	-0.78^{**}
	3–6 years	0.92^{****}	0.07^{ns}	0.75^{**}	-0.79^{**}
	6+ years	0.79^{**}	0.21^{ns}	0.92^{****}	-0.88^{***}
Irrigation pattern	Rainfed	0.93^{****}	-0.18^{ns}	0.94^{****}	0.19^{ns}
	Irrigated	0.76^{**}	0.32^{ns}	0.70^{*}	0.16^{ns}
Residue management	Removed	0.70^{**}	-0.62^{*}	0.88^{**}	-0.16^{ns}
	Retained	0.86^{****}	0.13^{ns}	0.81^{***}	-0.76^{**}
Crop rotation	No rotation	0.89^{****}	-0.31^{ns}	0.93^{****}	-0.90^{***}
	Rotation	0.86^{****}	0.33^{ns}	0.82^{**}	-0.31^{ns}

ET: evapotranspiration; MP: mean annual precipitation; MT: mean annual air temperature; NTD: no-tillage duration; ns: not significant.
* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
**** $P < 0.0001$.

3.2. Impacts of soil texture

The soil texture affected the NT wheat and maize yield, ET, and WUE (Fig. 5). NT significantly increased wheat yield by 5.6%, but not ET or WUE compared with CT in regions with coarse soil (Fig. 5A). However, NT had no effects on wheat yield, ET, or WUE compared with CT in regions with medium and fine soil (Fig. 5B, C).

NT had no effects on maize yield, ET, or WUE compared with CT in regions with coarse soil (Fig. 5D). NT significantly increased WUE, but not yield or ET, in regions with medium soil (Fig. 5E). NT had no effects on yield, ET, or WUE in regions with fine soil (Fig. 5F). The ln*R* of maize WUE was significantly positively related to the ln*R* of yield under all three soil textures (Table 3).

3.3. Impact of crop management practices

The effects of NT on wheat yield, ET, and WUE varied among the crop management practices (Fig. 6). NT had no effects on wheat yield, ET, or WUE in the first 1–3 years following NT implementation (Fig. 6A). Meanwhile, NT had no effects on wheat yield, ET, or WUE in the 3–6 years following NT implementation (Fig. 6B). A significant increase in wheat yield (6.6%), but not ET or WUE, was observed after NT had been implemented for 6+ years (Fig. 6C). NT had no effect on wheat yield, ET, or WUE under rainfed and irrigated conditions (Fig. 6D, E). NT significantly increased wheat yield (9.3%) and WUE (6.4%), but not ET, when residues were removed (Fig. 6F). NT had no effects on yield, ET, or WUE when residues were retained (Fig. 6G). NT significantly increased wheat yield (6.6%) and ET (1.8%), but not WUE, under no rotation conditions (Fig. 6H). Meanwhile, NT had no effects on yield, ET, or WUE under rotation conditions (Fig. 6I). The ln*R* of wheat WUE was significantly positively related with the ln*R* of wheat yield under different crop management practices, and there was a significant negative relationship between the ln*R* of wheat WUE and the ln*R* of wheat ET under residue removal (Table 3).

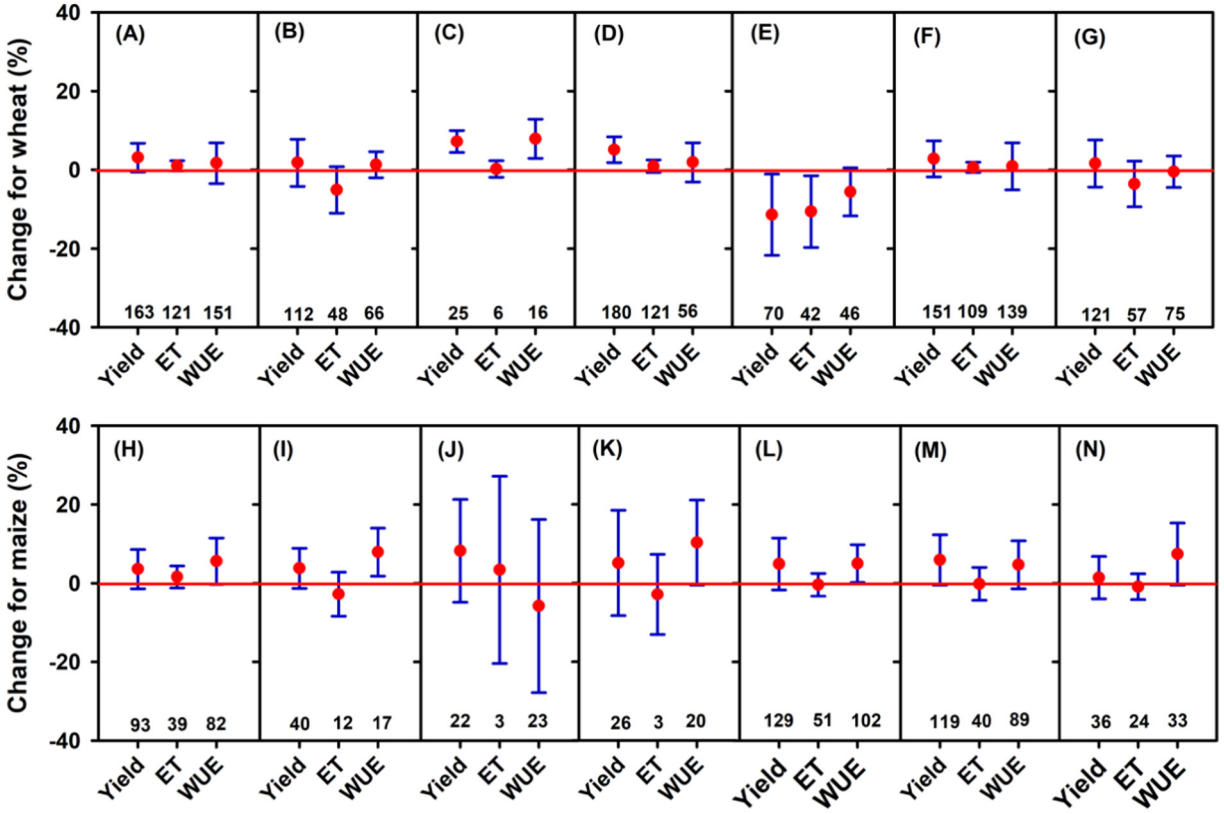

Fig. 4. Percentage changes in the yield, ET, and WUE of wheat between NT and CT in (A, northwestern China; B, northern China) different regions of China, (C, ≤400 mm; D, 400–600 mm; E, ≥600 mm) under different mean annual precipitations, and (F, ≤12 °C; G, >12 °C) with different MTs. Percentage changes in the yield, ET, and WUE of maize between NT and CT in (H, northwestern China; I, northern China; J, northeastern China) different regions of China, (K, ≤400 mm; L, 400–600 mm) under different mean annual precipitations, and (M, ≤12 °C; N, >12 °C) with different MTs.

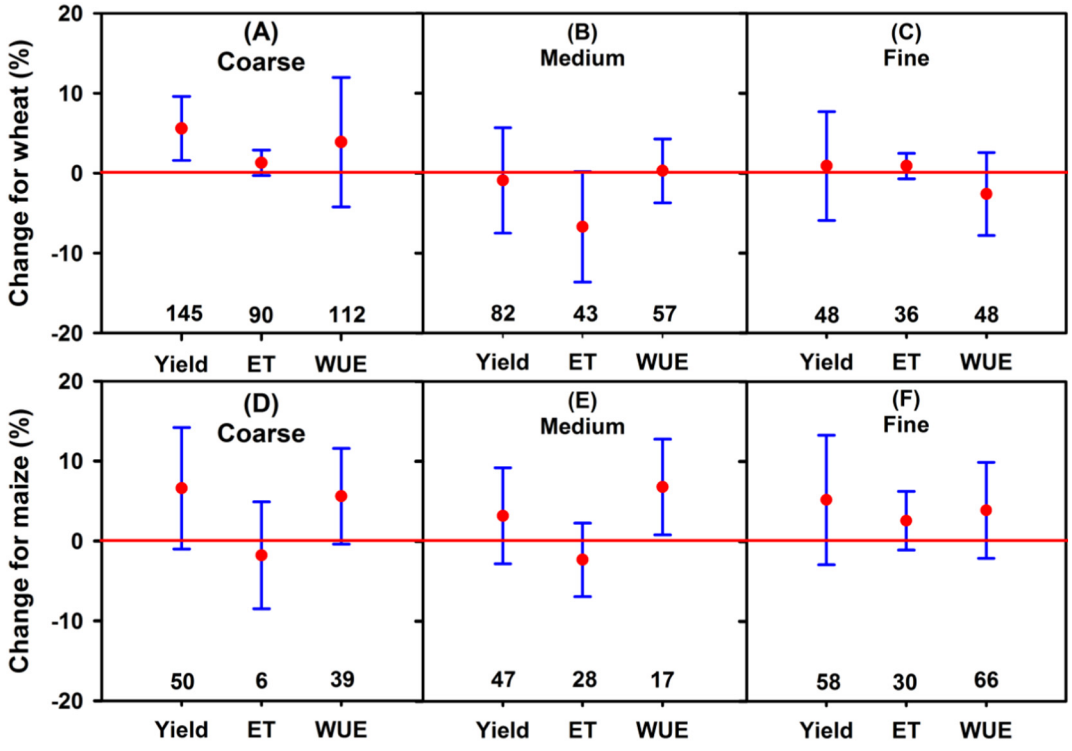

Fig. 5. Percentage changes in the yield, ET, and WUE of wheat and maize between NT and CT under different soil textures. The error bars represent the 95% CI. The number of observations is indicated below the CI.

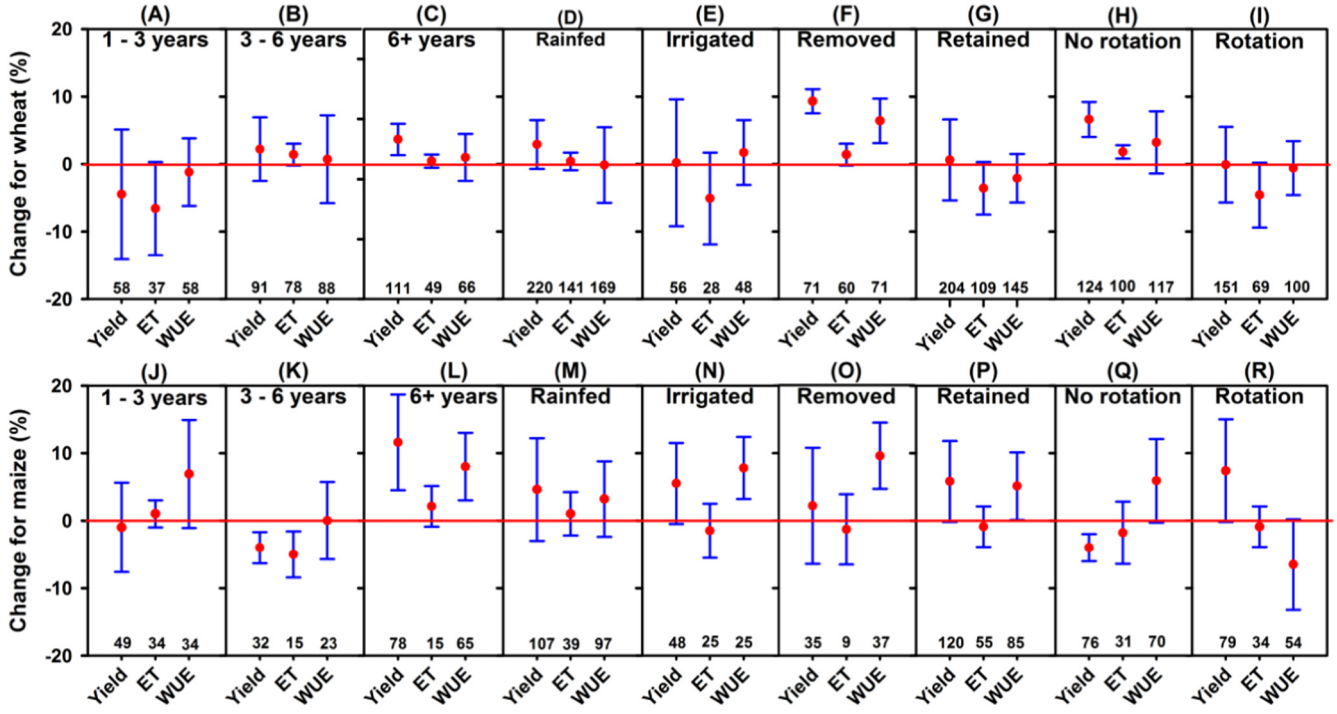

Fig. 6. Percentage changes in yield, ET, and WUE of wheat and maize between NT and CT under different (A–C, J–L) NT durations, (D, E, M, N) irrigation patterns, (F, G, O, P) residue management practices, and (H, I, Q, R) crop rotation practices. The error bars represent the 95% CI. The number of observations is indicated below the CI.

The yield, ET, and WUE responses to NT varied with crop management practices for maize (Fig. 6). NT had no effects on maize yield, ET, or WUE in the first 1–3 years following NT implementation (Fig. 6J). NT significantly decreased maize yield (4.0%) and ET (5.0%), but not WUE, compared with CT in the 3–6 yrs. following NT implementation (Fig. 6B). Maize yield (11.6%) and WUE (8.0%) were significantly improved when NT had been implemented for 6+ years, but there was no significant change in ET (Fig. 6L). NT had no effects on yield, ET, or WUE under rainfed conditions (Fig. 6M). There was a significant increase in WUE (7.8%), but not in yield or ET, under irrigated conditions (Fig. 6N). NT significantly increased maize WUE by 9.6% compared with CT when residues were removed, but had no effects on yield or ET (Fig. 6O). NT had no effects on yield, ET, or WUE when residues were retained (Fig. 6P). NT significantly affected maize yield, but not ET or WUE, under no rotation conditions (Fig. 6Q). NT had no effects on yield, ET, or WUE under rotation conditions (Fig. 6R). Meanwhile, we found a significant positive relationship between the ln*R* of maize WUE and the ln*R* of maize yield under different crop management practices, and the ln*R* of wheat WUE was significantly negatively related to the ln*R* of maize ET when NT had been implemented for 6+ years, when residues were retained, and under no rotation conditions (Table 3).

4. Discussion

4.1. Impacts by region, climate, and soil texture

When analyzing the effects of NT by regions, these results showed that NT significantly maize WUE in northern China, but no effects of NT on yield, ET and WUE in other regions (Fig. 4A, B, H, I, J). In north China, the accumulated temperature is insufficient to satisfy the needs of summer maize (Wang et al., 2018), and NT sowing could save several days to gain more accumulated temperature and make full use of rainfall for summer maize, resulting in the improvement of WUE as compared with CT sowing. For winter wheat, NT sowing significantly affected the quality of germination (Dong et al., 2007), resulting in low crop stands and poor seedling emergence (Zhang et al., 2014), and did not significantly improve or affect yield, ET and WUE. In northwestern China, only winter wheat or spring maize was grown and thus accumulated temperature was enough for crop growth. It is important to make full use of soil water and rainwater to produce greater yields in this region. Therefore, yield depends on both in-season rainfall and the amount of soil water stored in the soil before the growing season (Unger et al., 2006; Schillinger et al., 2008). Our results also showed the increasing effects of NT yield WUE were decreasing as the increase in rainfall amount for wheat and maize (Fig. 4C–E, K, L). In addition, the ET generally includes rainfall, irrigation, and soil water storage at the time of planting, soil water storage at the time of harvesting, and soil water storage depletion (Allen et al., 1998). Meanwhile, there was a significant ($P < 0.05$) correlation between the ln*R* of ET and soil water storage at the time of planting (Supplementary Table 3). Moreover, the results showed that the wheat yield increased significantly by 7.6% in the NT treatment in regions with an MP ≤ 400 mm, with a significant increase in WUE, in northwestern China (Supplementary Table 1). A significant ($P < 0.05$) correlation was observed between the ln*R* of ET and soil water storage depletion (Supplementary Table 3). Meanwhile, NT practices in some regions reduced crop productivity, resulting from the potential for cooler soil temperatures, compaction, and altered soil fertility requirements, which can inhibit crop establishment, affect root growth, and lead to nutrient deficiencies, respectively (Van den Putte et al., 2010; Ogle et al., 2012). (See Table 4.)

Soil factors impact no-till yields relative to tillage yields (Toliver et al., 2012), and the difference in soil texture resulted in different NT effects. NT significantly increased wheat yield under coarse soil texture, and maize WUE under medium soil texture, but there were no effects of NT on yield, ET and WUE under fine soil texture (Figs. 5A, C, E, 6F). In most cases, fine soil textures not only provide a good estimate for the soil-water potential, water holding capacity, and water availability for plant growth (Daryanto et al., 2016), but are also rich in organic matter, available nitrogen, available phosphorus, and available potassium. Conversely, coarse soil textures do not provide good biophysical or nutritional environments for crop growth. NT could improve nutrient supply, soil water infiltration and water holding capacity as compared with CT (Munkholm et al., 2013; Boeni et al., 2014). Thus, a greater

Table 4
Correlation coefficients between possible influential factors (MP, MT, and NTD) and the ln*R* of yield, ET, and WUE.

Factors	Wheat			Maize		
	Yield	ET	WUE	Yield	ET	WUE
MP	−0.26^{ns}	−0.39*	−0.15^{ns}	−0.13^{ns}	−0.16^{ns}	−0.21^{ns}
MT	−0.15^{ns}	−0.22^{ns}	−0.22^{ns}	0.31^{ns}	0.18^{ns}	0.56*
NTD	−0.24^{ns}	−0.21^{ns}	−0.21^{ns}	−0.30^{ns}	−0.21^{ns}	−0.18^{ns}

ET: evapotranspiration; MP: mean annual precipitation; MT: mean annual air temperature; NTD: no-tillage duration; ns: not significant.
* $P < 0.05$.

improvement of soil biophysical, water and nutritional environments by NT was observed in coarse or medium soil texture than fine soil texture, resulting in higher yield and WUE. Moreover, the effects of ET and WUE were positive for wheat in regions with coarse soil in northern China, but negative in regions with a fine soil texture (Supplementary Table 1). The results were similar for wheat in northwestern China (Supplementary Table 1). Overall, the results suggest that NT performs better in regions with coarse or medium soil textures.

4.2. Impacts of crop management practices

NTD was an important factor that affected the yield, ET, and WUE under NT. The wheat yield was gradually increased as the increase in the duration of NT, but the maize yield was firstly significantly decreased (3–6 years) and then significantly increased (Fig. 6A–C, J–L). In some cases, NT can increase weeds, and the organic matter which in return promotes the retention of certain pesticides (Novak et al., 1996) as compared with CT, which can result in yield declines, and it can take several years to uncover effective management practices for farmers that prevent weeds, pests, and diseases (Pittelkow et al., 2015b). Most of our data were from winter wheat, and summer maize study. The climate was dry in winter wheat season with little rainfall, weeds, pests, and diseases, whereas the summer maize season had more rainfall and higher temperature, resulting in more weeds, pests, and diseases under NT, which were reasons for the difference in effects of NT on yield from 1 to >6 years. In addition, Halde et al. (2015) reported that additional innovative soil and weed management practices are needed to make organic continuous no-till cropping system productive for a period longer than six years, in a cool subhumid continental climate.

No significant effects of NT on wheat ET and WUE were detected in the duration of NT from 1 to >6 years, while the maize ET and WUE were firstly decreased (3–6 years) and then increased (Fig. 6A–C, J–L). After transitioning from CT to NT, yield decreases in the early years are often attributed to the time required for soil to stabilize and for beneficial soil properties, such as increases in the soil available water capacity, soil carbon, and aggregate stability, to develop (Six et al., 2002; Kumar et al., 2012), and thus the effects of NT on maize WUE was decreasing and then increasing with the duration of NT. For maize ET, NT could increase the soil available water capacity in the short period, but the soil bulk density and compaction were increasing under NT in the long time (Nunes et al., 2015), and thus the soil available water capacity decreased, resulting in the loss of soil water and the increase in ET.

NT significantly increased maize WUE, did not affect yield and ET under irrigated condition, and no significant effects of NT on wheat and maize yield, ET and WUE under rainfed condition; NT did not affect yield, ET and WUE under irrigated condition (Fig. 6D, E, M, N). In rainfed regions, for winter wheat, it is best to make full use of limited rainwater, and several tillage practices (e.g., subsoiling and plowing tillage) are often used to decrease the soil bulk density, thus allowing soil to store more rainwater. However, NT can result in an increase in soil compaction and a deeper plow pan (Wang et al., 2014; Mu et al., 2016), creating stress in the soil environment that affects crop growth and rainwater storage, thus increasing ET. For summer maize, NT not only reduces costs, such as those associated with fuel, but also simplify planting management practices, resulting in advances in the maize planting date. Early planting significantly increased the yield of summer maize (Wang et al., 2017; Adnan et al., 2017; Wang et al., 2018) with and irrigation after sowing, thereby increasing the WUE (Fig. 6N). Our results also showed that NT significantly increased the WUE of maize under irrigated conditions (Fig. 6N).

NT with stubble retention increases the surface soil water content significantly (Huang et al., 2008), and retaining residues can reduce evaporation (Lampurlanés and Cantero-Martínez, 2006). The present meta-analysis showed that NT decreased wheat ET when crop residues retained (Fig. 6G), whereas NT increased wheat ET and WUE when crop residues removed (Fig. 6F). Conversely, several studies have claimed that one of the primary benefits of NT is the increase in WUE when residues retained (Hobbs et al., 2008; Farooq et al., 2011; Pittelkow et al., 2015b). In addition, NT increased the WUE of maize under the two crop residue management practices (Fig. 6O, P). The differences in these results were related to effects of crop residues on soil temperature. For winter wheat, the lower soil temperature under mulch in spring delayed the development of winter wheat, which on average reduced the final grain yield compared with no mulch; as a result, the overall WUE was not improved by mulch (Chen et al., 2007). In addition, too much summer maize residue often affects the quality of grain germination, thereby reducing the yield and WUE of winter wheat (Jia et al., 2010). For maize, crop residues improve the quality of grain germination, growth, and development due to an increase in soil temperature (Tolk et al., 1999).

Several studies have demonstrated the importance of crop rotation practices in minimizing the NT yield decreases in the context of conservation agriculture (An et al., 2010; Rusinamhodzi et al., 2011; Pittelkow et al., 2015b). However, the present study showed that NT significantly increased wheat yield when crops were not rotated, although when crops were rotated, NT did not affect yield and ET (Fig. 6H, I). Conversely, NT decreased maize yield under no rotation in this study (Fig. 6Q), and this result was consistent with previous reports (Pittelkow et al., 2015b). Most of data in this paper were extracted from studies on winter wheat and summer maize in China. The winter wheat-summer maize rotation system is the main cropping system in the North China region, with the limited rainfall mainly distributed in the summer maize season (Wang et al., 2016). The winter wheat used rainfall stored in soil during summer maize season, and thus more rainfall stored for winter wheat under no summer maize rotation, resulting in higher winter yield. The accumulated temperature is insufficient to satisfy the needs of summer maize (Wang et al., 2018), thus the crop residues from winter wheat rotation improved the grain germination, growth, and development of summer maize due to an increase in soil temperature (Tolk et al., 1999). Consequently, this study showed no rotation significantly increased wheat yield but decreased maize yield.

4.3. Limitations

It should be emphasized that although all variations were discussed in this paper, yield, ET, and WUE were affected by several factors that were not considered in this study due to insufficient information and limited data. For example, the prevalence of pests and diseases affects the NT effects, because pests and diseases are often worse under NT than CT; however, there was a lack of sufficient information to study this relationship. In addition, it is necessary to identify the importance of site-dependent controls and site-specific effects, and the interaction among factors should be considered because the grain yield and WUE responses to the tillage/crop residue practices vary greatly from year to year due to variable weather conditions. Overall, there is a strong interaction between tillage/crop residue methods and weather conditions (Wang et al., 2011).

5. Conclusions

The meta-analysis enabled the estimation of a range of agronomic and environmental factors affecting NT yield, ET, and WUE for wheat and maize in China. The results indicated that NT had no significant effects on the yield, ET, or WUE of wheat, but significantly increased maize WUE by 5.9%, which resulted from an increase in yield and reduction in ET. The responses of wheat and maize yield, ET, and WUE to NT varied by region, climate (precipitation and temperature), soil texture, NT duration, irrigation pattern, crop residue management practice, and crop rotation. Consequently, the environmental and management conditions should be considered when promoting the implementation of NT. This meta-analysis quantified the impacts of NT on yield, ET, and WUE based on the available scientific data, providing a basis for conducting synthesis analyses to support the development and improvement of NT wheat and maize management under various conditions in China. Our results can be used as a basis to model the interactions between agronomic inputs, quantify the productivity gains and production costs for maize and wheat, and determine optimal management practices.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.04.202.

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